# Environmental Assessment and Inversion Studies Based on Features of the Acoustic Vector Field in Shallow Water

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## LONG-TERM GOALS

The long-term goal of this research is to develop novel inversion techniques that use information contained in the acoustic vector field to provide more accurate and robust estimates of environmental parameters especially with sparse, compact and dynamic configurations of vector sensor arrays.

## OBJECTIVES

The specific objectives are to develop numerical algorithms based on novel theoretical treatments of the vector field in adjoint-model-based and other inversion schemes, and test them using synthetic data.

## APPROACH

As no real vector sensor data are available for this project, vector data are simulated for actual scenarios of environmental assessment in shallow waters. The selected experiments involve a large variety of source and receiver configurations with which validated, pressure-only, geoacoustic inversion results were obtained: broad signal frequency range (200 Hz–2 kHz), short to long ranges (1–15 km), full and sparse vertical receiver arrays (4–96 hydrophones), and fixed and dynamic configurations. This constitutes a realistic framework for experimenting with the inversion of acoustic wavefields or waveforms (time series) augmented with particle velocity information and evaluating the benefit of vector sensor technology in different scenarios.

Enhancements gained by utilizing the full vector field versus the pressure-only are studied for different schemes of combined geometrical (source localization/tracking) and environmental inversion using full-field signal processing, metaheuristics, adjoint modelling and stochastic filtering approaches. In contrast to global optimization approaches, an important attribute of the adjoint approach is that the inversion process itself is directly and optimally controlled by the physics (of acoustic propagation): an adjoint model run backpropagates the mismatch (residual) between the measured and modeled scalar and vector fields from the receiver array towards the source. The error field is then converted into an estimate of the exact gradient of the objective function with respect to any of the environmental model parameters, regardless of the dimensionality of the problem.

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14. ABSTRACT
**The long-term goal of this research is to develop novel inversion techniques that use information contained in the acoustic vector field to provide more accurate and robust estimates of environmental parameters especially with sparse, compact and dynamic configurations of vector sensor arrays.**

15. SUBJECT TERMS

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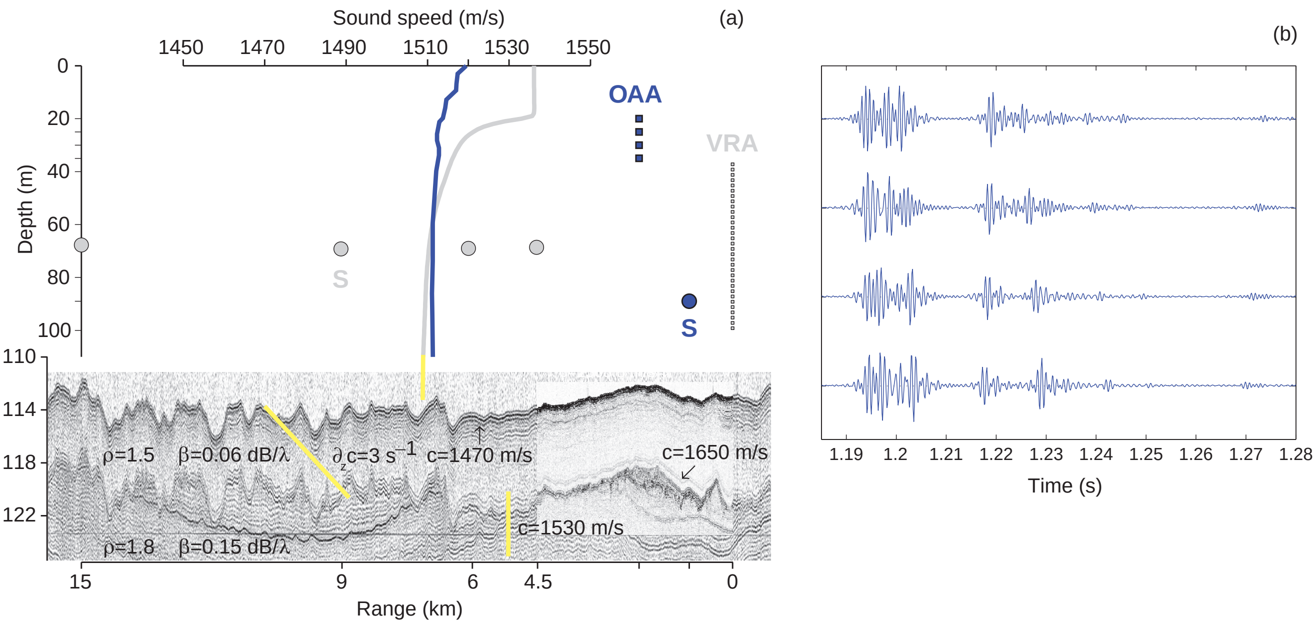


***Figure 1. Benchmark scenarios for testing vector-based environmental inversion. (a) Source-receiver geometries and water-column sound speed profiles from YS94 (gray) and MREA/BP07 (blue) experiments in the South Elba area, Italy. The seabottom consists of a 5–9-m thick soft clay layer overlying a silty clay subbottom; the indicated densities, compression wave attenuations and speed profile were obtained from the geoacoustic inversion of multitone and broadband pressure signals. (b) Sample of matched-filtered chirp signals received on a sparse ocean-acoustic array (OAA) deployed from a rubber boat; their frequency band is 0.8–1.6 kHz.***

Data synthesis is based on existing propagation models, wide-angle parabolic equation and normal modes, that are modified to compute pressure derivatives at a set of points.

## WORK COMPLETED

In the initial phase, vector data have been synthesized for simulated scenarios that are directly inspired from at-sea experiments. Experimental acoustic inversion work was revisited to identify shallow-water sites and measurement configurations of interest for studying the acoustic vector field. The chosen environment is the continental shelf area south of the Island of Elba, off the west coast of Italy, for which extensive ground truth data, oceanographical and geophysical, and pressure-based acoustic inversion results are available from NURC experiments in the nineties (YELLOW SHARK, 1993–1996),[1,2] and last year's Maritime Rapid Environmental Assessment experiment in the framework of a Joint Research Project (MREA, 2007).[3,4] The whole dataset now comprises a large amount of CTD profiles, seismic profiles, sediment cores and broadband acoustic pressure data worth tens of days. Among the large variety of acoustic runs the highly dynamic configurations of the 2007 experiment are of particular interest as they involve medium source frequencies (up to 1.8 kHz) and vertical arrays of 15-m length and four hydrophones only, for which successful inversion results were obtained recently.[5] This sets a baseline to compare predicted (or measured) performances, under the same environmental conditions, of similar array geometries when employing vector instead of pressure-only sensors.

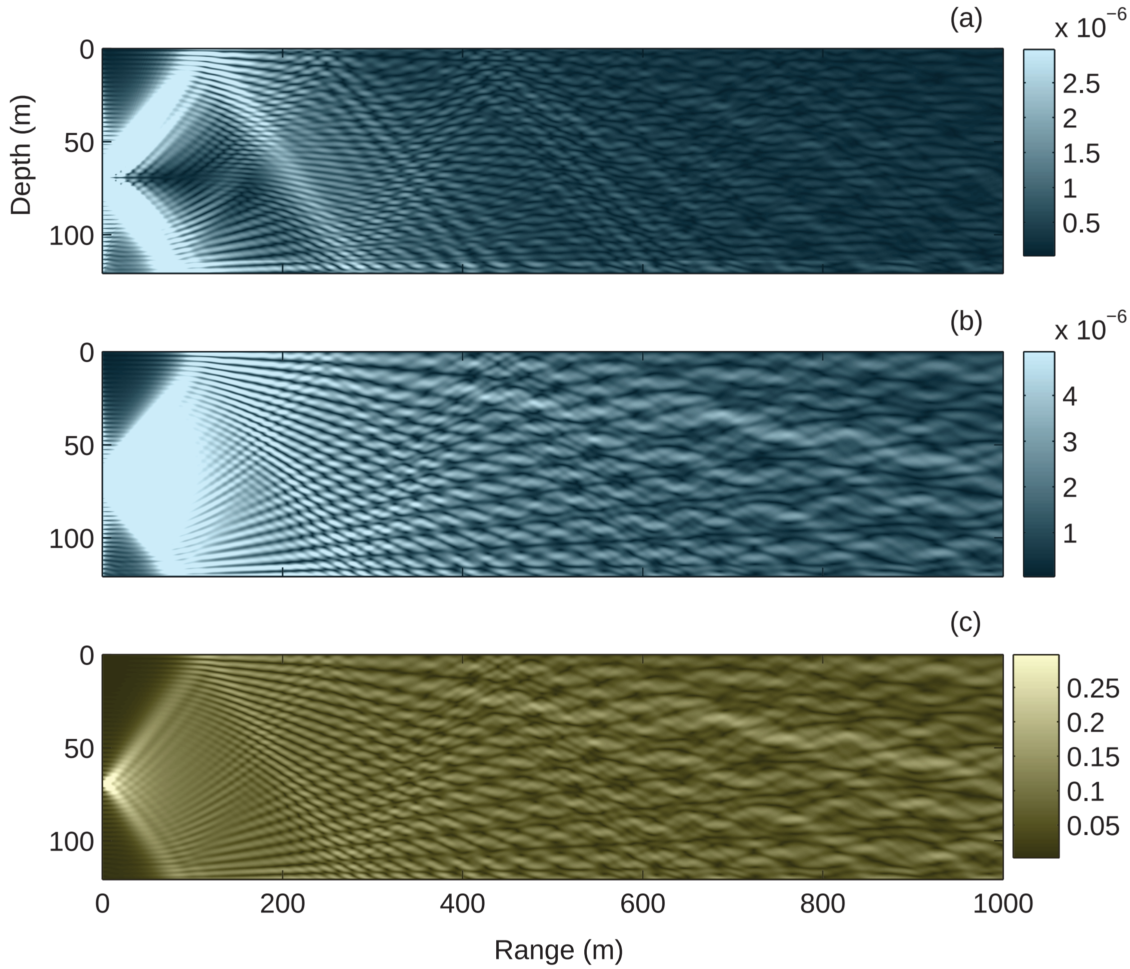


***Figure 2. Modeling the scalar and vector acoustic fields at 500-Hz frequency for the benchmark environment in Fig. 1 using the modified WAPE forward model of the adjoint-based inversion scheme. (a) Vertical (z) and (b) horizontal (r) components of the particle velocity, (c) Pressure.***

With regard to inversion methodology, the semi-automatic adjoint approach[6] has been extended for the treatment of acoustic particle velocity. Particle velocity is calculated locally from the pressure field and the cost function is augmented with the contributions of the vertical and radial components of the particle velocity. In continuation of the numerical and the previous analytical approach,[7] the propagation model that is chosen to demonstrate this extension to vector data is the wide-angle parabolic equation (WAPE) due to Claerbout. The resulting optimization scheme enables direct inversion for the geoacoustic parameters embedded in the non-local boundary conditions using particle velocity in addition to pressure. To verify the accuracy of the WAPE forward model in computing the pressure and pressure gradient fields (and of the numerical adjoint model), a comparison was made with reference models. For the benchmark acoustic and environmental conditions the modeling results were in good agreement. The numerical simulations were then carried out using the vector-augmented forward and adjoint WAPE models.

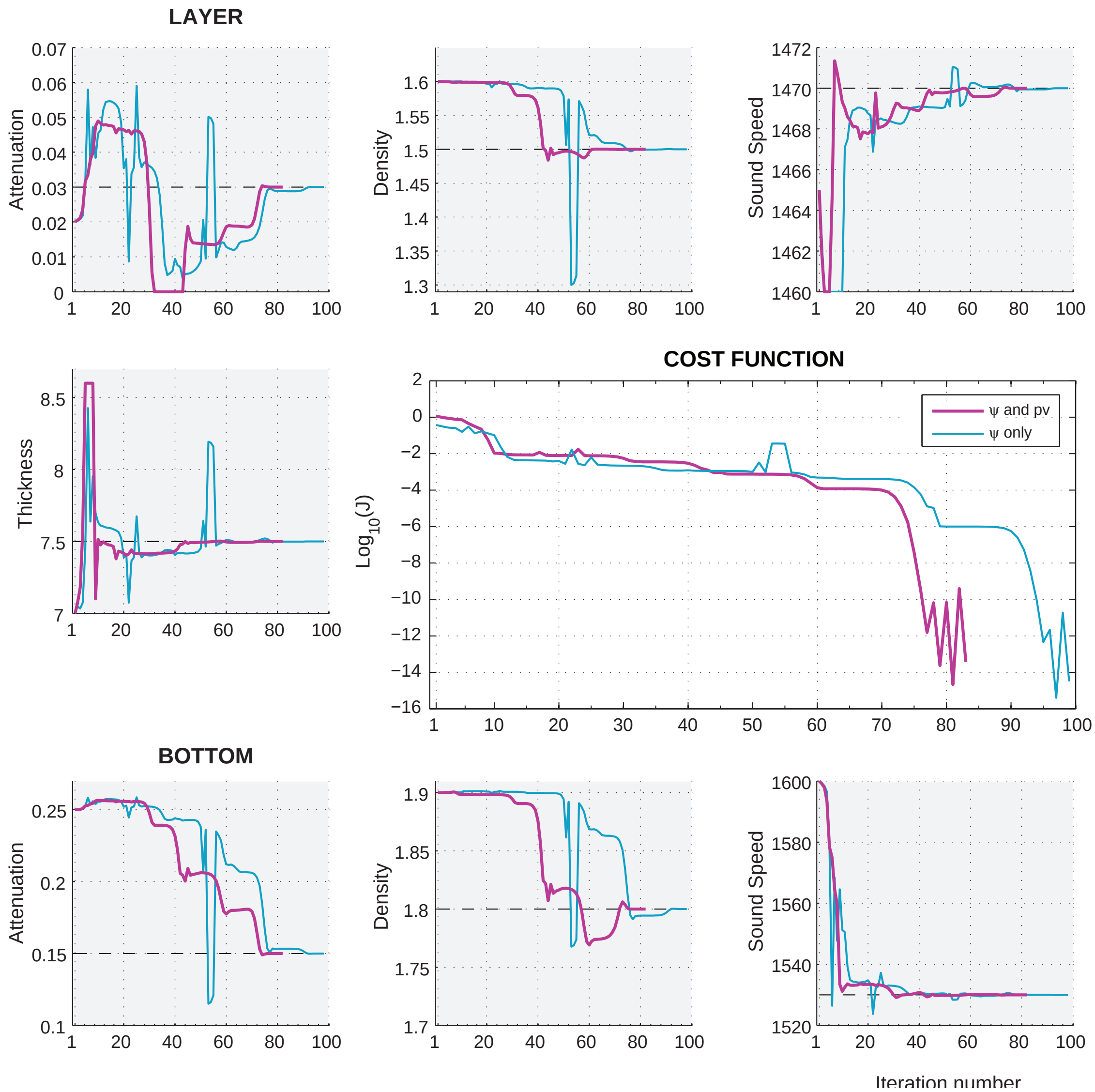


***Figure 3. Adjoint-based inversion for the seven geoacoustic parameters in Fig. 1 based on the acoustic pressure data only (cyan) and on both pressure and particle velocity data (magenta). Evolution of the control parameters and cost function is shown over the iteration number.***

## RESULTS

As a first illustrative example of vector-based environmental characterization using the adjoint method of optimal control we focus on the inversion for the seven geoacoustic parameters describing the sea bottom in Fig. 1(a) and a source-VRA range of 1 km. The inversion for the geoacoustic parameters is compared for the two cases of pressure-only and combined pressure and particle velocity fields. Generation of the adjoint is accomplished via gradient backpropagation by means of an algorithmic tool and the optimization process is carried out jointly across multiple frequencies (200 Hz, 400 Hz and 500 Hz).

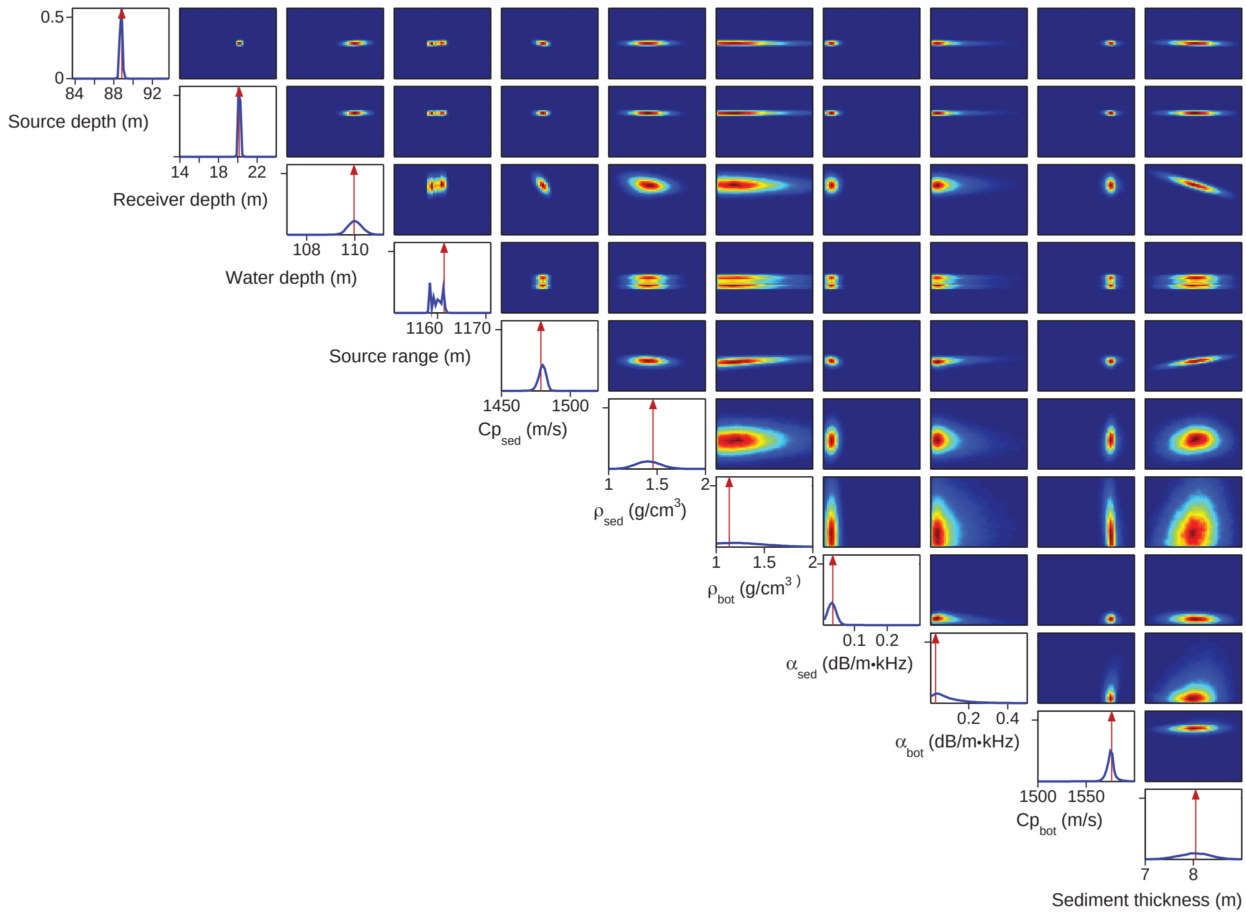


***Figure 4. Geoacoustic inversion results obtained from model-based matched filter (MBMF) processing of the sparse array signals shown in Fig. 1(b). The results are presented in the form of 1D-marginal PPD's (line plots) and 2D-joint marginal PPD's (color images) obtained with Bayesian inference for a set of 4 geometrical and 7 geoacoustic parameters.***

In Fig. 3, looking at the evolution of the individual geoacoustic parameters it can be seen that the combined inversion of pressure and particle velocity data exhibits a faster convergence towards the true parameter values. In both cases the evolution of the control parameters displays a parameter hierarchy which clearly relates to the relative sensitivity of the acoustic pressure field to the physical parameters. In the combined inversion the overall number of required iterations is reduced by 20% with respect to the pressure only inversion. Improvements are noticeable for all parameters in terms of convergence rate and smoothness of the curves. The densities converge close to their true values in less than half of the iterations which may be due to the vertical component of particle velocity. For a better comparison the evolution of the respective multi-frequency cost functions are also compared on a logarithmic scale. Also in this plot the decrease in the required number of iterations is clearly visible. It shoud be emphasized that the pressure-only version of the adjoint scheme has produced correct inversion results (both water column and bottom parameters) with at-sea data.[6]

Figure 4 shows geoacoustic inversion results obtained from measured channel impulse responses at a range of 1161 m comparable to the range used for the particle-velocity simulation results of Fig. 2. The good accuracy of the estimated parameters demonstrates that full-coherent, model-based matched-filter (MBMF) processing of pressure time series enables the use of very sparse and short arrays (here, 4 hydrophones, 5-m spaced). Furthermore, most of the signal energy used for the environmental inversion is above 1 kHz enabling the use of smaller and lighter sound sources which can be mounted on autonomous underwater (AUV) or remotely operated (ROV) vehicles. Hence these pressure-only experimental results constitute a baseline against which we will compare vector-sensor simulated results. For this purpose a synthetic particle-velocity counterpart of the real pressure data will be created using in-situ measured sound speed profiles and the geometric and geoacoustic parameter estimates of Fig. 3. To make the comparison valuable, a realistic noise model for the particle velocity still needs to be determined.

In parallel to the adjoint work novel inversion/tracking schemes based on Bayesian signal processing including unscented Kalman filter (UKF) and ensemble Kalman filter (EnKF) are being developed at U.L.B. for environmental inversion applications, especially for full-field acoustic tomography and geoacoustic inversion in shallow water using dynamic configurations. These schemes do not yet incorporate particle velocity in the measurement vector but in principle can be modified to provide a functionality similar to the adjoint scheme.

One of the critical questions that remains to answer is does the use of vector sensor data not only decrease the time to reach a convergent solution, but does it also reduce the uncertainty in the geometrical or environmental parameters? Since the adjoint-based inversion scheme is computionally very efficient it is conceivable to carry out an uncertainty analysis using a probabilistic approach we are currently developping. Nevertheless metaheuristics will also be considered as it produces widely-accepted histogram plots (posterior probability distribution, 1D and 2D marginals) for a reliable comparison of pressure-only and particle-velocity solutions and their respective accuracies. The abovementioned Bayesian filtering approach may be used as well.

## IMPACT/APPLICATIONS

As the US Navy continues to develop new sensor systems, the results of this analysis focused on environmental assessment is of critical importance for systems engineers looking for optimal use of vector sensor technology. Simulation results of optimal control theory applied to the intensity field show promising new ways to exploit the information gained from vector sensors for environmental assessment.

The developed adjoint-based inversion processor is expected to be particularly useful in real-time applications with dynamic configurations for which there is a need to continuously update both the geometrical and range-dependent environmental parameters. Additional work is required, however, to determine the applicability of such methods to real particle-velocity data sets in real environments. Furthermore, the experimental results recently obtained with very sparse pressure-only arrays during the MREA/BP07 sea trials provide a baseline to assess the potential benefit brought by vector sensor technology for the purposes of environmental inversion under operational conditions.

## RELATED PROJECTS

ONR has been funding experimental work on measurements and analysis of the vector field focused on sonar standard issues. Work on the processing of data from arrays of vector sensors is being carried out by various groups under the framework of the PLUSNet program, among others. The present project covers additional aspects valuating the ability of new processing techniques for environmental inversion in shallow water.

A project of collaboration with Univ of Rhode Island (URI) is proposed in the framework of a PhD research project dealing with the processing of SAX'04 vector sensor data collected by the Canadians at DREA, under the guidance of Jim Miller and Kevin Smith. A first meeting to discuss the collaboration was held end of October with Kevin Smith and Steven Crocker, following a coordinated visit to Microflown company on vector sensor technology.

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